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Time and Power Domain Interference Management for LTE Networks with Macro-cells and HeNBs

Yuanye Wang^{*} and Klaus I. Pedersen[†]

^{*}Aalborg University, [†]Nokia Siemens Networks – DK-9220 Aalborg East – Denmark

Email: ywa@es.aau.dk

Abstract—Interference management for co-channel deployment of macro-cells and closed subscriber group (CSG) home-cells (HeNBs) are studied. We especially address the downlink macro-layer coverage-hole problem, where HeNBs may create too high interference to nearby macro-users, unless active interference management is applied. Interference management techniques based on HeNB power setting and partial Time Domain (TDM) muting of HeNBs are studied. Cases with TDM muting require optimization of the macro-cell packet scheduler, including taking into account that the interference level varies significantly at the users as function of the enforced muting pattern for the HeNBs. During subframes where HeNBs are muted, some interference is still generated due to the fact that signals like common reference signals are still to be transmitted. It is therefore studied how much the HeNB interference from muted subframes shall be reduced for TDM muting to perform better than schemes with simple HeNB power reduction.

I. INTRODUCTION

Heterogeneous network with mixed macro-cells and Home enhanced NodeBs (HeNBs) has attracted many research interests these days. While retaining the benefit of planned macro-cell layer, the HeNBs can be deployed in a rather flexible manner, boosting the performance in hot-spot area and offloading the macro-cell system.

The HeNBs are small base stations (BSs) transmitting at much lower power than the macro-BS. They can be deployed by the end-users and are typically installed following the Closed Subscriber Group (CSG) mode [1]. Therefore, macro-users that are not configured with a CSG list of the HeNBs cannot be served by the HeNBs. The HeNBs can use a different (usually higher) carrier frequency than the one used for macro-cells. This avoids the interference between macro-cell and HeNBs, but requires more bandwidth. Alternatively, the same carrier could be shared by both macro-cell and HeNBs. The co-channel deployment of both systems reduces the spectrum requirement, but invokes interference between them. In the downlink transmission, macro-users close to HeNBs tend to receive heavy HeNB interference, leading to the well known macro-cell coverage-hole problem [2][3]. Meanwhile, the HeNB-users are less affected by the macro-BS, due to the fact that they are close to their serving base station. Therefore, it is of vital importance to protect the macro-cell performance in the presence of co-channel CSG HeNBs. The protection can be realized by interference management at both the HeNBs and the macro-cells.

Several methods for improving the macro-cell performance in this scenario have been developed. E.g., HeNB power

control, Time Domain (TDM) muting and Frequency Domain (FDM) escape carrier [4]-[7]. A summary of possible solutions considered in 3GPP can be found in [8]. All these techniques offer the trade-off between macro and HeNB performance. As to HeNB power control, different approaches have been used. Some automatically adjust the power based on e.g., interference or path loss measurement, while some others statistically set the HeNB transmit power to an appropriate level. The former relies on the HeNB Network Listening Mode (NLM) to obtain the real-time measurement. This study uses the simple method of the static HeNB power setting. TDM muting applies to the HeNBs, which prevents (mutes) the HeNBs from transmitting on certain subframes. Meanwhile, the macro-cells are transmitting on all subframes. Due to the muting of the HeNBs, the macro-users will experience rapid interference variation in the time domain according to the muting pattern. This requires the macro-cell packet scheduler to use the proper user Channel State Information (CSI) feedback that matches the current muting status.

The performance of HeNB power control and TDM/FDM resource partitioning has been studied separately in the open literature [1]-[7]. However, the comparison between the different solutions or the combination of them in one system has been rarely studied [9]. In this paper, we will evaluate the trade-offs offered by static HeNB power setting and TDM muting in the downlink transmission of an LTE-Advanced system. The purpose is to identify the method that offers the best trade-off, and to provide guidelines for the network deployment.

The paper is organized as follows: Section II introduces the different interference management options considered in this paper; Section III describes the heterogeneous network scenario and the simulation assumptions; In Section IV, the performance for the investigated techniques is evaluated and compared against each other. Finally, Section V concludes the paper.

II. INTERFERENCE MANAGEMENT OPTIONS TO IMPROVE MACRO-CELL PERFORMANCE

A. Static HeNB power setting

Static HeNB power setting is a simple method to protect the macro-user performance. By transmitting at lower power, HeNBs will generate less interference to the macro-cell. Meanwhile, their performance will be degraded because the

interference coming from macro-cells remains the same. As specified in [10], the maximum HeNB transmit power is 20 dBm, and a lower-limit of 0 dBm is used in this paper.

B. Time Domain (TDM) muting at HeNB

TDM applies to the HeNBs and restricts them not to transmit on certain subframes. These subframes are referred to as the Almost Blank Subframe (ABS) and the rest of the subframes are non-ABS [11]. Note that the word ‘almost’ comes from the fact that the Common Reference Signals (CRS) are still sent on these muted subframes. Due to these common reference signals, the HeNBs still generate interference to the macro-cells, even if they are muted.

In order to apply TDM muting, both the macro-cells and the HeNBs should be aware of the muting pattern, and strict time-synchronization between the two network layers is required. The macro-cell scheduler will primarily schedule the users close to non-allowed HeNBs when they are muted. The cost of TDM muting is degraded HeNB performance, which decreases linearly with the muting ratio. Fig. 1 shows a case with TDM muting, where HeNBs are muted twice every 8 subframes, and the macro-BSs are transmitting on all subframes.

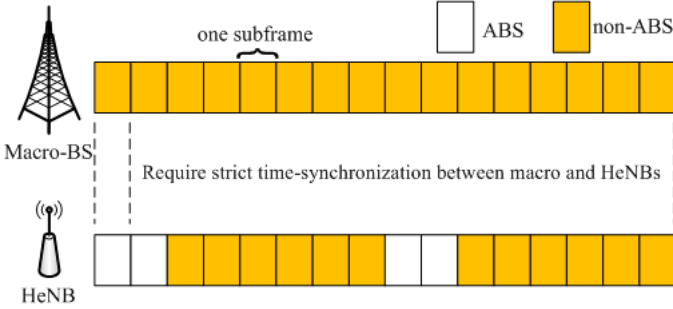


Fig. 1. Macro-cell and HeNB transmitting pattern with TDM muting.

C. CSI management and packet scheduling at macro-cell

TDM muting causes the macro-user experienced interference level to vary between ABS and non-ABS. In order to fully exploit the benefit of TDM muting at macro-cell, the base station needs to use the CSI that is measured with the same muting status as the current transmission instant. In the downlink, CSI is measured at the user side and then reported to the base station, subject to feedback delay. According to [12], it is possible to configure the LTE-Advanced users with two CSI measurement patterns, one for ABS and the other for non-ABS. With these separate CSI measurements, a normal Proportional Fair (PF) scheduler could efficiently prioritize the users that are close to non-allowed HeNBs when muted, and vice versa. However, the LTE-legacy users do not support separate CSI feedback for ABS and non-ABS. Only the LTE-Advanced users are considered in this paper.

III. SCENARIO DESCRIPTION AND SIMULATION ASSUMPTIONS

The performance of the different techniques is evaluated in a quasi static downlink multi-cell system level simulator that follows the LTE specifications defined in [11], including detailed implementations of Layer-2 packet scheduling,

Hybrid Automatic Repeat Request (HARQ) and link adaptation functionalities. The link to system mapping is based on the exponential effective metric model [13]. The investigated scenario is depicted in Fig. 2, where a dual-stripe building is present in a traditional macro-cell network.

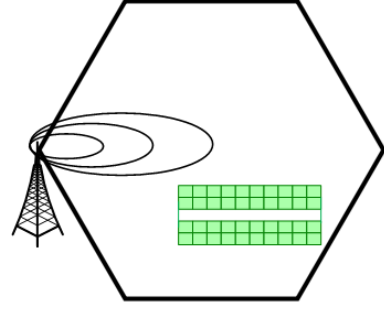


Fig. 2. Heterogeneous deployment with mixed macro-cells and HeNBs.

The macro-layer is modeled according to the macro-cell case #1 [14]. Among all the macro-cells, only the center one is simulated, and one dual-stripe building is randomly placed within the coverage of this center cell. The surrounding ones are used to generate time continuous interference across the full bandwidth. The dual-stripe building is modeled following the guideline in [15], which is a 6-floor building with 40 rooms per floor (separated into two stripes by a 10 m wide corridor). The size of each room is 10x10 m². There is 20% probability for each room to have a HeNB installed, and each HeNB is associated with an activity factor of 50%. Overall, 24 HeNBs are actively transmitting from the dual-stripe building. To generalize our findings with different HeNB densities, a higher activity factor of 100% is also tested, giving 48 active HeNBs.

The simulation process is conducted as a series of simulation runs (200 runs with 1 second duration per run) with a constant number of users per cell. During each run, the HeNBs are randomly activated in the dual-stripe building, with random locations inside each room. One HeNB-user is generated within each room that has an active HeNB. It is connected to the HeNB that is located within the same room. Macro-users are generated within the whole cell coverage area, with 8 users inside the dual-stripe building and 2 outside. The simulation parameters are summarized in Table I.

For TDM muting, the transmission of common reference signals on ABS results in non-zero interference power, which is modeled as offset dB lower than HeNB interference on normal subframes (non-ABS). Let I_{HeNB} (in dBm) denote the HeNB interference on non-ABS, the interference coming from HeNBs with ABS can be represented by $I_{HeNB} - offset$.

A 2x2 Multi-input Multi-output (MIMO) with rank adaptation [16] and Interference Rejection Combining (IRC) [17] is used for the performance evaluation. The received signal has the form [18]:

$$y = h_s P_s x_s + \sum_k h_k P_k x_k + n \quad (1)$$

where h denotes the N_{rx} by N_{tx} channel between the serving

base station and the user; P is the transmission amplitude (square root of the transmission power); vector x with size N_{tx} is the transmitted modulation signal and vector n (size N_{rx}) is the thermal noise at the receiver side. s and k represent the index for the serving and interfering base stations; $N_{tx}=N_{rx}=2$ is the number of transmit and receive antennas.

TABLE I: SYSTEM SIMULATION SETTINGS

Parameter	Setting / description
Test scenario	3GPP Macro-cell case #1 (19 sites with 500 m inter-site distance; 3 cells per site; reuse 1) with overlaid dual-stripe HeNB building
Bandwidth and carrier frequency	10 MHz bandwidth at 2000 MHz frequency
Sub-frame duration	1 ms (11 data plus 3 control symbols)
MIMO configuration	2 by 2 with rank adaptation and IRC
Transmit power	Macro: 46 dBm; HeNB: 0~20 dBm
CSI feedback delay	6 ms
Layer-2 packet scheduler	Proportional fair
Modulation and coding schemes	QPSK (1/5 to 3/4) 16-QAM (2/5 to 5/6) 64-QAM (3/5 to 9/10)
HARQ modeling	Ideal chase combining with maximum 4 transmissions
1st transmission BLER target	10%
Traffic type	Full buffer
User speed	3 kmph
Minimum distance between user and BS	Macro: 35 m; HeNB: 1 m
Minimum BS – user coupling loss	45 dB
Urban-dense femtocell modeling parameters [15]	
Number of rooms per row	10 (in total 40 rooms per floor)
Number of buildings per cell	1
Number of floors per block	6
HeNB deployment ratio	20%
HeNB activation ratio	50% or 100%
Probability of macro-user being indoor	80%
Interference offset between ABS and non-ABS	10 dB (the worst case) to ∞ dB (ideal case, no HeNB interference on ABS)

The IRC receiver makes use of a weighting vector w for the interference cancellation. It also minimizes the mean square error (MMSE) of the received signal, and is hence referred to as the MMSE-IRC receiver in [18]. The weighting vector is:

$$w = P_s h_s^H (P_s h_s h_s^H + \sum_k P_k h_k h_k^H + \sigma_n^2 I)^{-1} = P_s h_s^H R^{-1} \quad (2)$$

In (2), σ_n^2 is the noise variance and I is the N_{rx} by N_{rx} identity matrix. The capability of IRC receiver for interference cancellation depends on the accuracy of the weighting factor w , and in turn, the spatial correlation matrix R . Several methods for estimation R have been considered in 3GPP [19][20]. In this study, we assume the ideal IRC with perfect knowledge of the correlation matrix. Furthermore, the interfering signals are modeled as rank-1 transmissions.

The performance is collected separately for the macro-cells and the HeNBs. The following performance indicators will be used for the evaluation:

- G-factor: the ratio of the total received wideband signal power and the interference plus noise power at the receiver side. It includes the effects of path loss and

shadow fading, but is average over fast fading.

- Average cell throughput: the cell throughput averaged over all simulated cells from all simulation runs.
- Cell edge user throughput: the 5%-tile worst user throughput from all simulated ones.

IV. PERFORMANCE

A. Performance with only HeNB power reduction

The G-factor distribution for macro-user and HeNB-users is plotted in Fig. 3, with different levels of HeNB transmit power. When HeNBs are transmitting at the maximum power of 20 dBm, they generate heavy interference to macro-users and cause macro-layer coverage-hole. For instance, more than 20% of the macro-users have G-factor lower than -10 dB. Without special protection, these users will suffer from very low data rate. Decreasing the HeNB transmit power level improves the macro-user G-factor, but at the same time reduces the G-factor for HeNB-users. The case with zero HeNB transmit power ($-\infty$ dBm) corresponds to ideal ABS muting of the HeNBs and has the best macro-user G-factor. As compared to the case with full HeNB interference (non-ABS), the 5%-tile G-factor is increased from -28 dB to -2.6 dB. The gain is smaller for cell-center users, which is only 2.7 dB at 90%-tile.

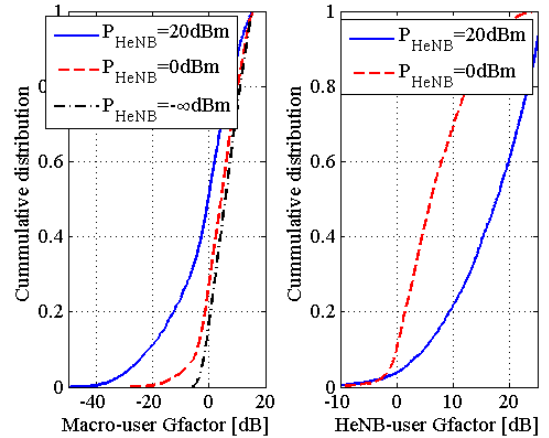


Fig. 3. G-factor distribution for macro-users and HeNB-users.

Fig. 4 summarizes the average cell throughput (the blue axes) and cell edge user throughput (the red axes) for macro-cell and HeNBs. The performance with different HeNB transmitting powers is denoted with different markers. As shown in Fig. 4, a trade-off between the performance of the two layers is obtained by changing the HeNB transmit power. The trade-off is more obvious in the cell-edge user throughput than in the average cell throughput. Reducing the HeNB power from 20 dBm to 15 dBm increases the cell edge macro-user throughput by 149% and causes only 12% reduction of the cell edge HeNB-user throughput. For the average macro-cell throughput, a much lower gain of 5% is observed. It is also noticed from fig. 3 and fig. 4 that, despite the poor macro-user G-factor when HeNBs are transmitting at maximum power (20 dBm), some data can still be conveyed to the users. E.g., the 5%-tile worse macro-user achieves a throughput of

150 kbps, at G-factor of only -28 dB. This is due to the fact that one macro-user is mainly exposed to one dominating HeNB interference, which can be effectively cancelled by the IRC receiver.

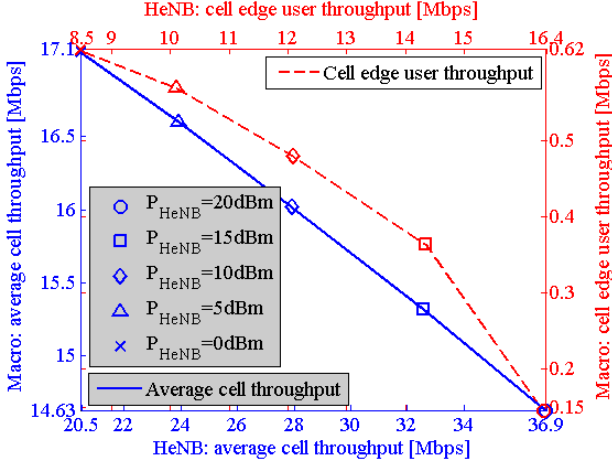


Fig. 4. Trade-off between macro-cell and HeNB throughput when using different HeNB transmit power.

B. TDM muting with power control

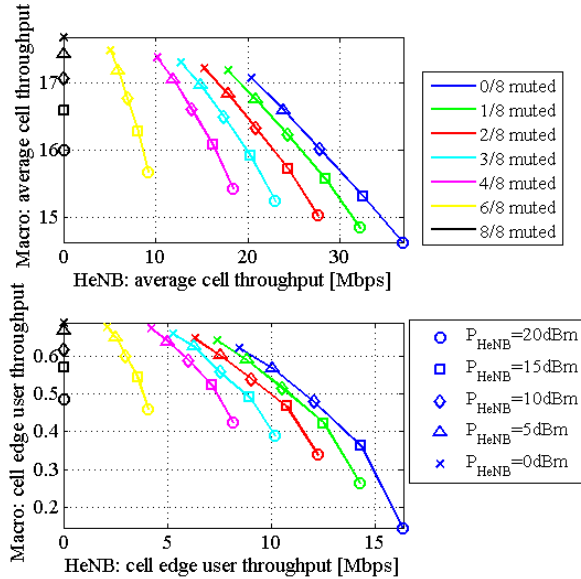


Fig. 5. Performance of power reduction and TDM muting, with realistic interference on ABS (Offset=10dB).

In real systems, TDM muting suffers from the effect of non-zero HeNB interference for ABS, due to the common reference signals. For a system with 2 transmit and receive antennas, common reference signals account for around 10% of the total transmission load. Therefore, the ABS is assumed to have a 10 dB lower interference level than non-ABS. Fig. 5 shows the performance with different TDM muting ratios. For each muting ratio, different HeNB transmit power levels are also evaluated and the performance is marked with different markers. The case when 0% muting corresponds to no TDM muting. As can be seen from Fig. 5, with the same macro-cell performance, a higher muting ratio offers poorer HeNB

throughput. It is therefore concluded that with realistic HeNB interference on ABS, the best trade-off is achieved with only power reduction. In order for TDM muting to be beneficial, a further reduction of the HeNB interference on ABS is needed. This is possible via advanced receivers using CRS-interference cancellation algorithm.

C. TDM muting with different HeNB interference levels on the muted subframes (ABS)

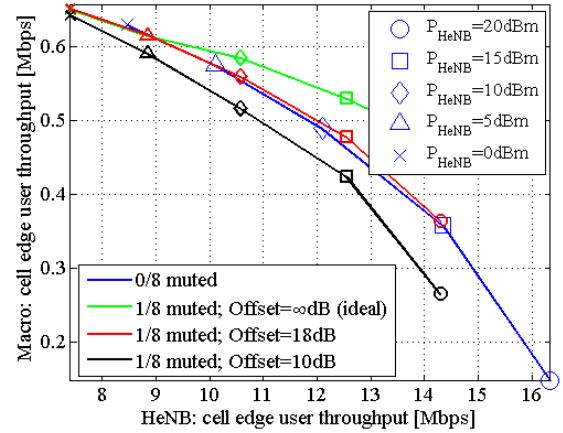


Fig. 6. Cell-edge user throughput for power reduction and TDM muting, with different power offsets for ABS.

Fig. 6 shows the cell edge user throughput for macro-cell and HeNBs. TDM muting is evaluated with different interference offsets for ABS. The performance of purely power reduction (0/8 muted) is also plotted for reference. The muting ratio of 1/8 is used here. As can be seen from Fig. 7, if ideal muting is assumed for ABS, TDM muting will achieve a much better trade-off than power reduction. As an example, TDM muting with $P_{HeNB} = 20$ dBm has the same HeNB cell edge user throughput as reducing the HeNB power to 15 dBm. Meanwhile, it has 31% higher cell edge macro-user throughput than power reduction. TDM muting remains beneficial if ABS can be controlled to have at least 18 dB lower interference than non-ABS.

Additional performance results are reported in Fig. 7 where the full macro-user and HeNB-user throughput distribution is plotted for cases with static HeNB power reduction and/or TDM muting. As shown, the worst macro-cell performance is experienced when the HeNBs are transmitting at their maximum power of 20 dBm without TDM muting. Correspondingly, HeNB-users with this configuration achieve the best performance. When 1/8 of the subframes are ideally muted (zero HeNB interference on ABS) and HeNBs transmit at 20 dBm, the HeNB-user performance is reduced to the same level as would be experienced with $P_{HeNB} = 15$ dBm and no muting. However, TDM with ideal muting outperforms the case with no muting in the sense that it offers better macro-cell performance. This is in coherence with the findings in Fig. 6.

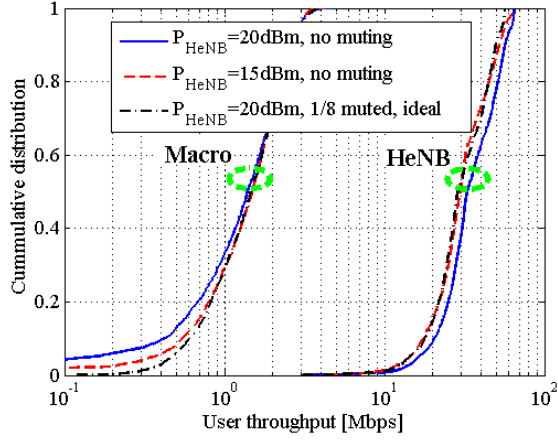


Fig. 7. CDF of macro-user and HeNB-user throughput with power reduction and/or TDM muting.

From Fig. 7 it is also noticed that the HeNB-users experience approximately ten-fold higher throughput than macro-users. Therefore, macro-cell performance is clearly the limiting factor in the overall system performance. In such a network, what is important is to improve the cell edge macro-user throughput, such that the macro-cell coverage-holes are removed.

D. Requirement on HeNB ABS interference reduction with different muting ratios and different numbers of HeNBs

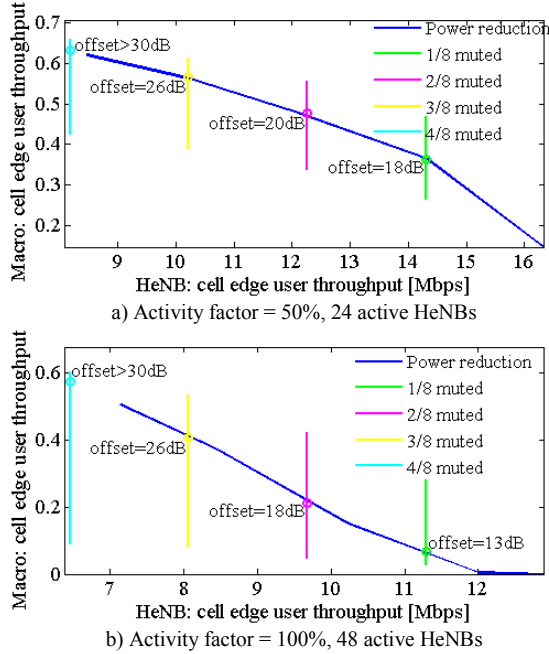


Fig. 8. Performance with static HeNB power reduction or TDM muting. Different HeNB densities have been evaluated.

Fig. 8 shows the trade-off between macro-cell and HeNB cell edge user throughput using static power reduction or TDM muting. The performance is evaluated with different HeNB activity factors, and hence different number of HeNBs.

For static power reduction, different HeNB transmit power levels from 0 dBm (the left-most point) to 20 dBm (the right-most point) have been considered. For TDM muting, various muting ratios from 1/8 to 4/8 are evaluated together with

different HeNB interference reduction (*offset*) on ABS. With TDM muting, reducing the HeNB interference on ABS improves the macro-cell performance while maintaining the same HeNB performance, and hence the curves are vertical. For each muting ratio, the bottom-point corresponds to an offset value of 10 dB, and the top-point corresponds to ideal muting with *offset*= ∞ dB. The intersection point between one vertical curve and the curve for power reduction indicates the minimum required ABS interference offset for TDM muting (with a certain muting ratio) to outperform simple HeNB power reduction.

As can be seen from Fig. 8a, for TDM muting to be beneficial, the HeNB interference offset for ABS shall increase with the muting ratio. With 50% activity factor, it has been obtained before that an offset of 18 dB is enough for muting ratio 1/8. This increases to 20 dB for muting ratio 2/8 and higher than 30 dB when 4/8 of the subframes are muted.

With more HeNBs (100% activity factor), HeNB power reduction becomes less efficient in eliminating the macro-cell coverage hole than TDM muting. This is evident from the larger gap between ideal muting and power reduction in Fig. 8b than in Fig. 8a. As a consequence, a smaller offset value is required for TDM muting to outperform HeNB power reduction. As indicated in Fig. 8b, the required offset is 13 dB for muting ratio 1/8. But it quickly increases to beyond 30 dB for muting ratio 4/8.

It is also observed that a high HeNB density significantly penalizes the macro-cell edge user throughput and requires a high muting ratio and/or power reduction to solve the coverage-hole problem. However, judging from the requirement on ABS interference reduction, TDM muting with muting ratio beyond 50% is not recommended.

E. Comparison between power reduction and TDM muting

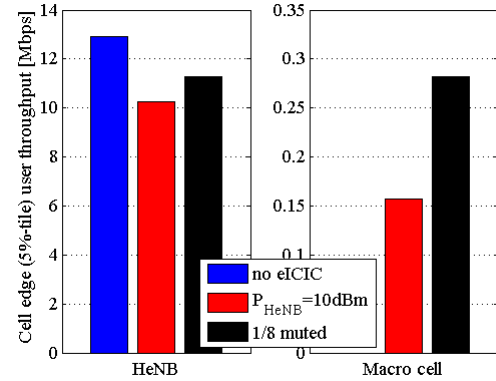


Fig. 9. Cell edge user throughput in HeNB and macro layer, with HeNB power reduction, TDM muting or no eICIC.

In this subsection, the performance between HeNB power reduction and ideal TDM muting is compared with each other. For HeNB power reduction, a low HeNB transmitting power of 10 dBm is used; for TDM muting, the muting ratio is chosen as 1/8. The case of no muting and 20 dBm HeNB transmitting power is kept for reference. A dense HeNB deployment scenario of 100% activity factor (i.e., 48 active HeNBs) has been considered.

Fig. 9 shows the cell edge user throughput for the HeNB layer and the macro layer. As expected, reducing HeNB power or applying muting in time domain reduces the performance of the HeNB layer. Meanwhile, the macro-layer performance is significantly improved. While the baseline case of no eICIC cannot transmit anything to users in cell edge, using HeNB power reduction or TDM muting increases the cell edge user throughput to 160 kbps and 280 kbps, respectively.

If we consider a Quality of Service (QoS) constraint in user throughput, the users getting lower throughput than the QoS target will be considered as in outage. With a target of 200 kbps, the outage probability when using different techniques can be obtained. This is shown in Fig. 10. As can be seen from Fig. 10, the HeNB users have much higher throughput than the QoS target, and hence have zero outage probability. The network performance is mainly limited by the macro-layer, which has 19% outage probability when no eICIC scheme is applied. By using only 10 dBm power for HeNBs, the outage probability is reduced to 6%. Mute the HeNBs once every 8 subframes has the lowest outage probability of less than 2%.

From both Fig. 9 and Fig. 10 it can be seen that, with zero interference on muted subframes, TDM muting achieves better macro-layer performance at less degradation of the HeNB-layer performance, and hence it is more promising than simple HeNB power reduction.

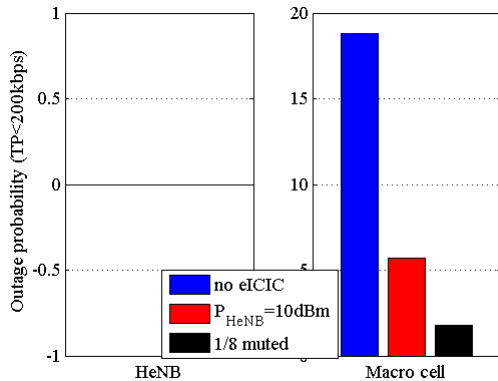


Fig. 10. Outage probability in HeNB and macro layer, with HeNB power reduction, TDM muting or no eICIC.

V. CONCLUSION

In this paper we have investigated interference management methods based on HeNB power reduction and TDM muting in heterogeneous networks. It is observed that TDM muting can achieve a better trade-off between the macro-cell and HeNB performance, on condition that the interference from almost muted subframes is significantly reduced as compared to the normal subframes. Otherwise, simple HeNB transmit power reduction is preferable for protecting co-channel macro-users.

The performance of interference management is also sensitive to the deployment scenario, e.g., the HeNB density. A high HeNB density requires higher muting ratio and/or HeNB power reduction in order to maintain good macro-cell performance. However, from the obtained results, it is not recommended to use TDM muting of more than 50% of the

subframes.

It shall be noted that TDM muting requires strict network time-synchronization between macro and HeNBs. It also leads to rapid time domain fluctuation of the interference level, and therefore CSI measurement restrictions are assumed for the terminals, so separate CSI measurements are available for muted and un-muted subframes from the users. However, legacy terminals are not expected to support such measurement restrictions. As future work, we would also like to study the performance of TDM interference management, taking into consideration the effect of control channel performance before drawing final conclusions on the concept. The case of more realistic interference sources with rank adaptation will also be addressed.

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